Estimation of Sensitivities in Samples with Wrong-sign Contamination

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I. INTRODUCTION

While reviewing the code used to estimate the ν_μ disappearance sensitivity of the LAr1-ND for events which contain wrong-sign contamination we located a bug. This has led to a change in the sensitivities which were presented in Ref. [1]. This note will explain how we measure the sensitivity for ν_μ disappearance in LAr1-ND, document the bug and its fix, and show the resulting change in sensitivities. Throughout this note it will be assumed that the wrong-sign contamination will not oscillate.

II. SENSITIVITY CALCULATION

To measure the sensitivity to the oscillation signature in N total events we will remove the number of wrong-sign events, n_{ws}. We will use the fraction of events which are right-sign, $f = 1 - f_{ws} = 1 - ({}^{n_{ws}}/_{N})$, to remove the wrong-sign contamination. Such that the total number of right-sign events, n, is equal to:

$$n = N \times f = N \times (1 - f_{ws}). \tag{1}$$

Once we have removed the wrong-sign contamination from our sample the sensitivity is estimated by comparing two cases:

1. When the right-sign events are allowed to oscillate, n_{osc}
2. When the right-sign events are not allowed to oscillate, n_{null}

To determine the sensitivity to detecting an oscillation signal we construct the χ^2 in bins of neutrino energy:

$$\chi^2 = [n_{osc} - n_{null}]E^{-1}[n_{osc} - n_{null}] \tag{2}$$

where E is our diagonal error matrix. The elements along the diagonal are the total uncertainty for each bin, j, of neutrino energy and are defined as:

$$E_{jj} = (\sigma^j_{stat})^2 + (\sigma^j_{syst})^2 + (\sigma^j_{ws})^2. \tag{3}$$

In the FD we constrain σ^j_{syst} using the statistics measured in the ND. Then σ^j_{ws} is the uncertainty on the number of wrong-sign events in bin j which are removed before doing the χ^2 fit. This is defined as:

$$\sigma^j_{ws} = \sigma^j_f \times f^j_{ws} \times N^j \tag{4}$$

where σ^j_f is the uncertainty on the fraction of wrong-sign events in bin j, f^j_{ws} is the fraction of wrong-sign events in bin j, and N^j is the total number of events in bin j. When the sample contains no wrong-sign contamination ($f_{ws} = 0$) this uncertainty reduces to 0.

III. ANTINEUTRINO SENSITIVITIES

When determining the sensitivity in antineutrino running we will have to deal with a large uncertainty brought on by the wrong-sign contamination in the antineutrino beam (we assume that the wrong-sign contamination does not oscillate). The contamination ranges between $\sim$ 30% (at low neutrino energy) and $\sim$ 90% (at high neutrino energy) of the sample. Luckily, the problem of constraining the rate of wrong-sign events which come in the $\bar{\nu}$ beam has been studied by MiniBooNE [2]. The MiniBooNE collaboration has found they could measure the fraction of wrong-sign event to a precision of $\sim$ 15%. This allows us to confidently set $\sigma_f = 15\%$.

We can then look at two cases to determine our sensitivity to oscillations:

1. Using the "bathtub" LAr1-ND in combination with MicroBooNE we measure the sensitivity without any suppression of the wrong-sign contamination

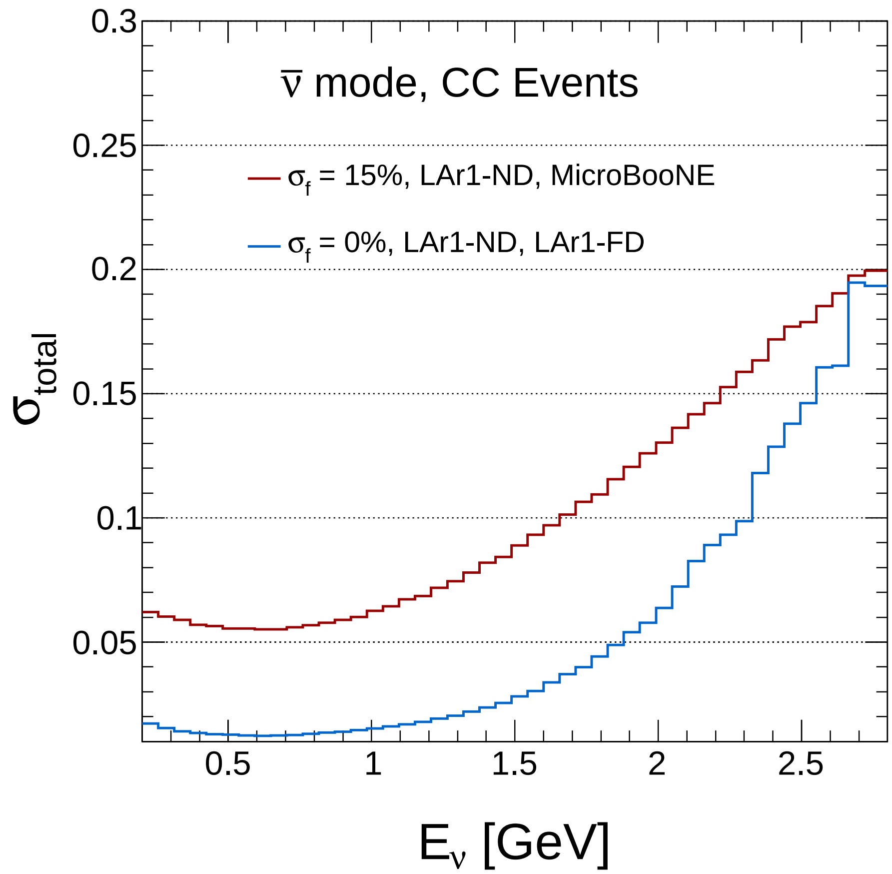

FIG. 1. Comparison between the total uncertainty for option 1 ($\sigma_f = 15\%$) and 2 ($\sigma_f = 0\%$) listed in Sec. III. While this is a comparison of the total uncertainty while including the effects from the contamination of wrong-sign events it also is comparing the different detector setups used between the two options.

2. Using a combination of the large volume magnetic LAr1-ND with a magnetic LAr1-FD with the ability to reject all of the wrong-sign contamination

This is a further change from Ref. [1] where all three detectors where used in both cases. A comparison of the total uncertainty for the two options can be found in Fig 1. When compared to Fig. 5 we see a similar but not identical change in the uncertainty. The first case is a fairly pessimistic view of what this analysis could achieve. Ref. [2] points out that LAr TPCs should benefit from a modest ability to reject this wrong-sign background for events with a contained muon. Based upon how the track terminates we will be able, in some cases, to determine the charge of the muon. This effect is currently neglected and we focus on the situation where we have 0% rejection of this wrong-sign background.

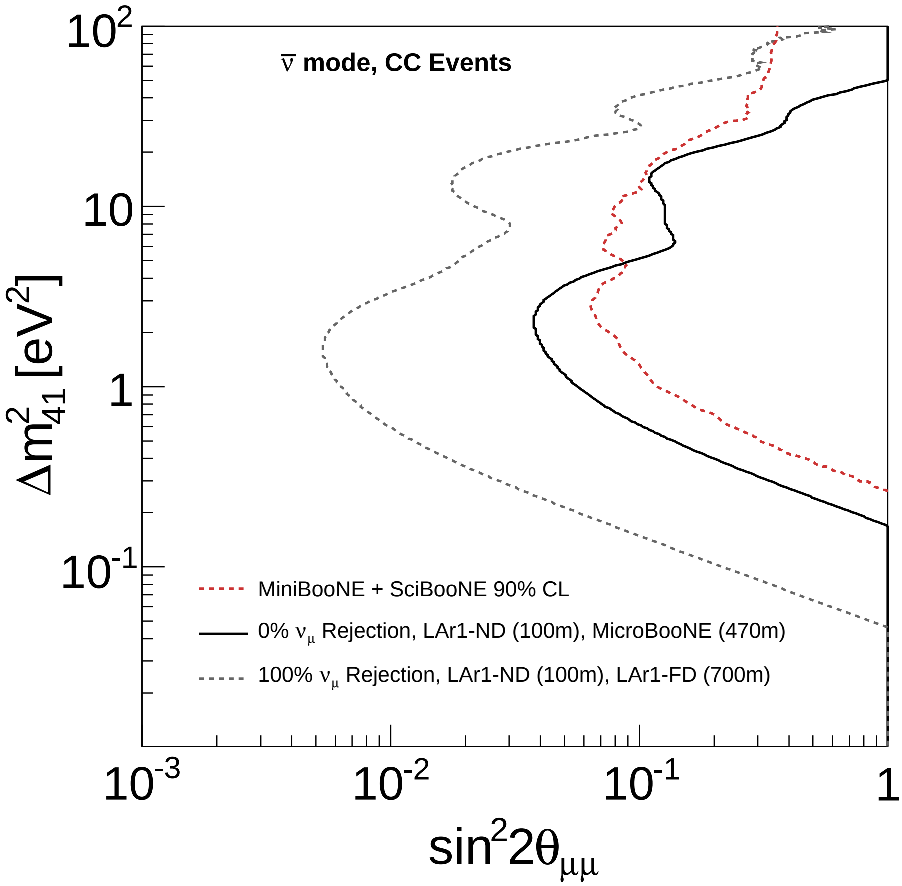

FIG. 2. The sensitivity to measure the $\bar{\nu}_\mu$ disappearance as a function of Δm^2_{41} and $\sin^2(2\theta_{\mu\mu})$ with 10×10^{20} POT in the two different LAr1 programs. The case with 0% wrong-sign rejection is composed on a non-magnetic LAr1-ND and MicroBooNE. The case with 100% wrong-sign rejection uses a magnetic LAr1-ND (large volume, no downstream spectrometer) and LAr1-FD.

This leads to a comparison between two curves, with and without rejection of the wrong-sign background. These sensitivities are shown in Fig. 2. Once we have corrected the "bug" (discussed in Sec. V) we can see a dramatic change in the sensitivity from what was reported in Ref. [1]. The gray-hatched line has remained the same because this curve was unaffected by the "bug" discussed in Sec. V. The source of this sizable shift in the sensitivities comes from the large f_{ws} in this sample. When this is correctly accounted for it leads to a large increase in the overall uncertainty on each bin.

IV. SENSITIVITIES AND NEUTRAL CURRENT CONTAMINATION

When measuring the effect on the sensitivities from neutral current (NC) events we will apply the same methods as for the wrong-sign contamination. When analyzing samples which have NC contamination we are aided by there being a small fraction of such events. Less than 10% of our final sample comes from NC events. We are still constrained by a large uncertainty on this fraction. For our studies we have used $\sigma_f = 30\%$. This is taken as a flat systematic over all bins of neutrino energy.

To compute the sensitivity we assume that the NC contamination will not oscillate. While we will not be able to distinguish between charged pions and muons if their tracks exit the TPC volume, for tracks which terminate inside the volume we will be able to exploit information about the event to distinguish charged pions from muons. Since the rate at which we will be able to separate charged pions from muons inside the volume has not been determined we choose two different pairs of pion misidentification rates, ε^{π}, and muon selection efficiencies, ε^{μ}. The size of ε^{π} will then reduce the fraction of NC events, thus increasing our sensitivity. The two scenarios used are:

1. a realistic assumption: $\varepsilon^{\pi} = 20\%$ and $\varepsilon^{\mu} = 80\%$

2. an even assumption: $\varepsilon^{\pi} = 50\%$ and $\varepsilon^{\mu} = 50\%$

A comparison the total uncertainty for these options and for events without any NC contamination can be seen in Fig. 3. We can translate these into two sets of sensitivities which are then compared to the sensitivity which does not include any NC contamination. Fig. 4 shows this comparison, and when this figure is compared directly to what was presented in Ref. [1] we see a significant suppression of the sensitivities for the sample containing large NC contaminations.

V. THE BUG

While preparing the figures for Ref. [1] σ_{ws} was not correctly computed. Specifically, the definition of σ^j_{ws} was altered to exclude N^j. This has a large effect on the χ^2 calculation, especially when f_{ws} is large. This has now been corrected so that the uncertainty being used to estimate the sensitivities fully accounts for the uncertainty on the wrong-sign contamina-

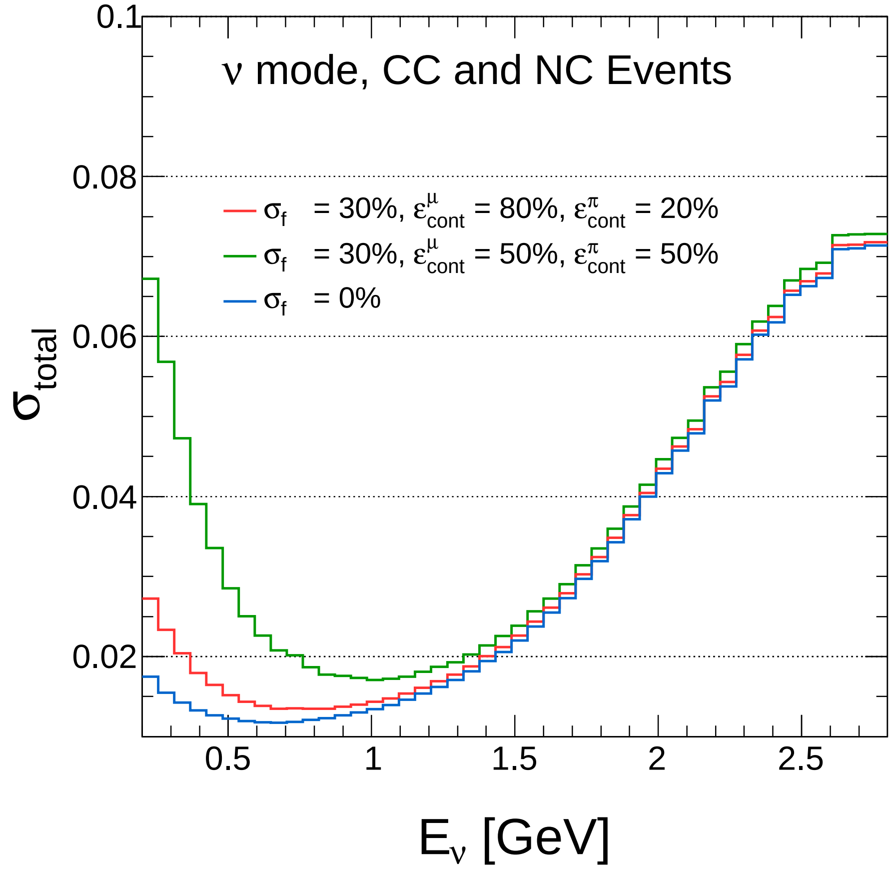

FIG. 3. Comparison between the total uncertainty for option 1 and 2 listed in Sec. IV ($\sigma_f = 30\%$) and with no NC contamination ($\sigma_f = 0\%$).

tion. A comparison between the correct estimation of the total uncertainty and what was used in Ref. [1] is shown in Fig. 5.

VI. CONCLUSIONS

After locating and correcting the bug in the code used to determine the sensitivity of this analysis we find a significant change in the sensitivities presented as in Ref. [1]. This bug only affects those sensitivities which take into account background contaminations. The new resulting sensitivities are presented here and show a large reduction in the sensitivity with an increase in the background contamination. This fundamentally changes the conclusions in Ref. [1] and points to the substantial gains that can be achieved by suppressing these

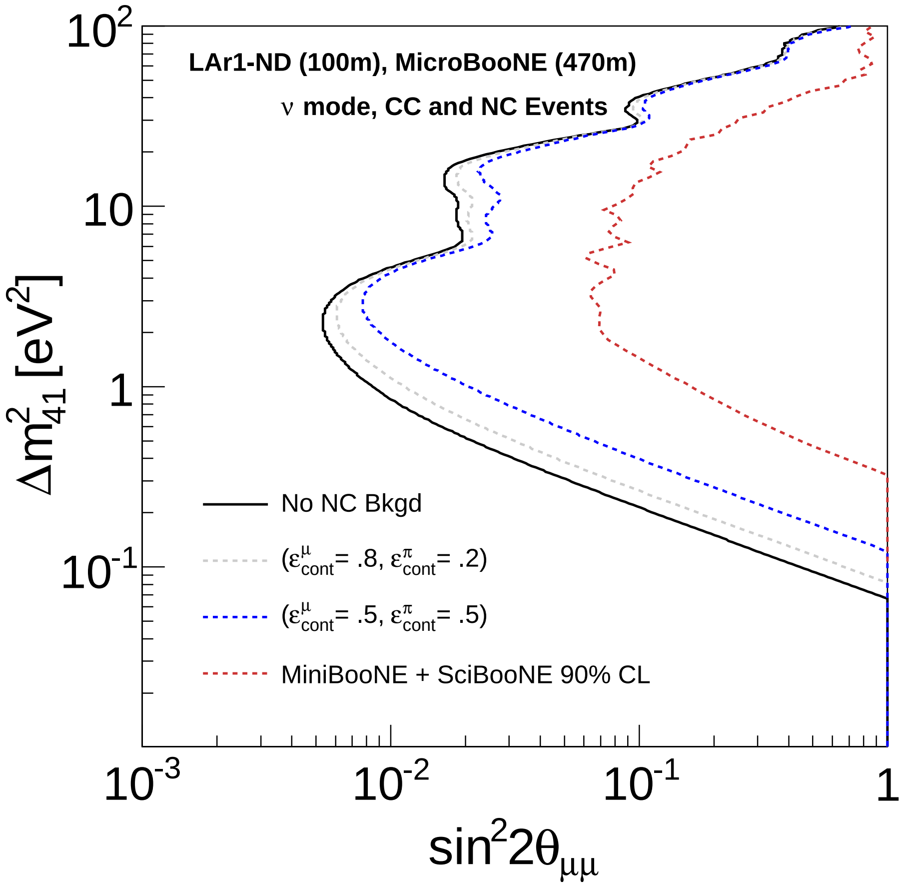

FIG. 4. The sensitivity to measure the ν_μ disappearance as a function of Δm^2_{41} and $\sin^2(2\theta_{\mu\mu})$ with 6.6×10^{20} POT in MicroBooNE and with 2.2×10^{20} POT in LAr1-ND. When including the NC contamination to these events it results in a significant decrease in the possible sensitivity.

backgrounds.

[1] J. Zennamo, "Muon Disappearance Analysis Update", `http://lartpc-docdb.fnal.gov:8080/cgi-bin/ShowDocument?docid=1147` (2013).

[2] A. A. Aguilar-Arevalo *et al.* [MiniBooNE Collaboration], Phys. Rev. D **88**, 032001 (2013).

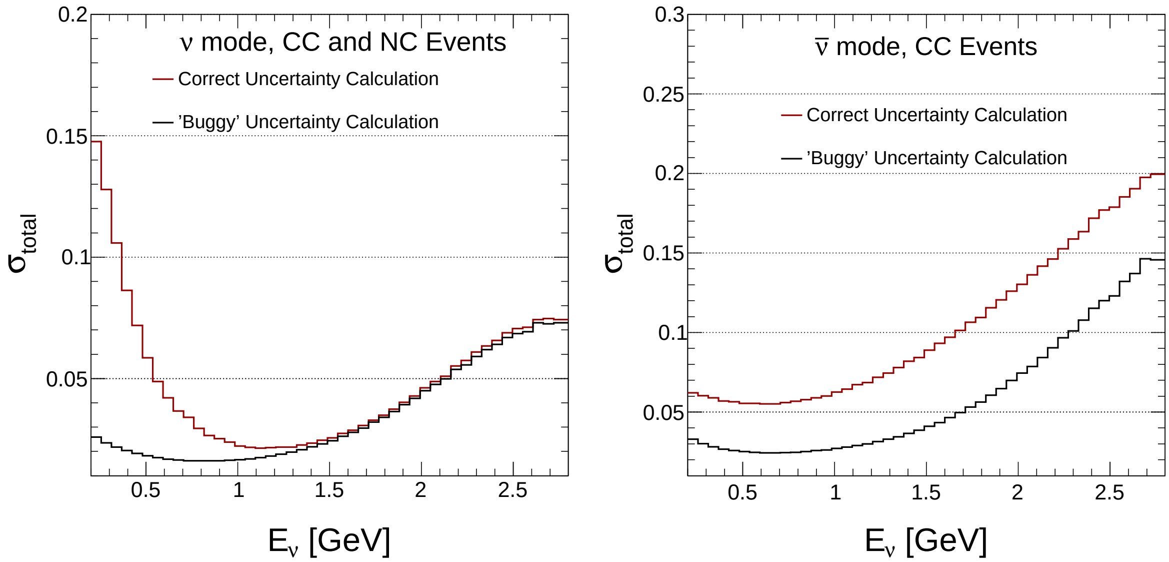

FIG. 5. A comparison of the total uncertainties ($\sqrt{E_{jj}}$) estimated with and without the "bug" in bins of reconstructed neutrino energy. For the case of neutral current events in our sample we treat it as a wrong-sign contamination and we use the assumption that $\varepsilon^{\pi} = 80\%$ and $\varepsilon^{\mu} = 20\%$. We see a large increase in the uncertainty between the two cases.